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WP8 | MODELLING OF TOPOGRAPHIC SIGNAL

NEW SOFTWARE FOR THE ANALYSIS OF LANDSCAPE RESPONSE TO FAULTING

(Deliv 8.3)

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1. Introduction

Slow active faults are inherently defined as faults that produce little displacement over geological time. This characteristic implies that the signature of such fault at the surface is very subtle and thus difficult to detect. One challenging strategy to tackle the problem of identifying elusive tectonic records is the careful inspection of sensitive features in the landscape through quantificational methods. This approach assumes that even the faintest modification of the ground surface due to tectonics affects the development of recognizable landscape features. The ever increasing availability of computing machines and detailed Digital Elevation Models (DEM) encourages the usage of dedicated software to speed up the geomorphic/tectonic analysis and mapping. The next sections will illustrate a suite of three original software tools dedicated at analysing the response of the landscape to the tectonic forcing caused by slip at depth on seismogenic faults. This process of analysis includes the following main steps: (1) detection of sensitive landscape features; (2) parameterisation of seismogenic faults; and (3) modelling landscape evolution.

The three programs (1) ARD; (2) FaultStudio; and (3) LEM were designed to help the tectonic geomorphologist to go through the above three steps of analysis.

Section 2.1 will illustrate the ARD 1.0 program, a tool dedicated to the detection of river anomalies. A river is said to behave anomalously when it assumes any of its usual forms in a place that is not suited for that form. Examples of river anomalies are the abrupt horizontal sweeps of the channel course in an apparently flat area and the degradational to aggradational - or vice versa - shifts in an apparently regularly sloping valley. Schumm and Khan (1972) apply analogical models to analyse the behaviour of rivers under several conditions of surface displacement due to tectonics and find out that recognisable patterns of the river course develop systematically. Their concepts have been applied in tectonic studies worldwide, especially in fast deforming regions. Burrato et al. (2003) presents one of the few study carried out in a region, the Po Plain (northern Italy), where tectonic deformation is thought to be slow. They illustrate a rich variety of anomalous features that can be explained by sustained slip on buried faults. Following their examples the ARD program provides a practical way to detect, constrain and quantify a river anomaly simply by using a DEM. Results from the ARD program can be easily mapped using any Geographic Information System.

Section 2.2 will illustrate the FaultStudio 1.0 program, a tool designed to devise self-consistent earthquake faults, manipulate their parameters and store the results into a database. Faults are schematically represented by a rectangular plane. Their seismic potential is estimated through widely accepted analytical and empirical relationships between fault size and moment magnitude (Kanamori and Anderson, 1975; Wells and Coppersmith, 1994). A fully-featured and friendly Graphic User Inter-

face (GUI) allows the user to make very fine adjustments of the fault characteristics. Creation and modifications of faults is done in a GIS environment (MapInfo) so that the user can easily check, in real-time, all the manipulations before his/her own geographically-consistent geological and geophysical data.

Among the various features of the program, an important function is the capability of handling a quick procedure to calculate the surface displacement produced by a single event of slip on a fault (Okada, 1985) and produce a contour map of the results without leaving the GIS environment. This capability complements the functionalities of the ARD program (section 2.1) by allowing the user to make a preliminary but unavoidable comparison between landscape features and ground surface modification due to earthquakes.

Section 2.3 illustrates the LEM 1.0 program, a tool that goes further into the analysis of the landscape response to faulting. It allows the user to simulate the landscape evolution under various conditions of tectonic forcing and to test the reliability of the tectonic-geomorphologist's conjectures.

The modelling of landscape evolution is a way to explore the interactions between endogenic and exogenic processes and may be used to compare the relative roles of various processes in shaping the Earth's surface. As part of a forward modelling approach LEM can be used to generate synthetic landscapes that simulate, as realistically as possible, the development of landscape features over time in an area affected by the compound activity of geomorphic processes and faulting. The usage of a modelling approach is particularly important in the study of very remote areas or where the tectonic signal is very subtle and, then, difficult to investigate through field surveys.

The typical question that this program can help to answer is: "what is the minimum slip rate required to a thrust fault to make its associated anticline grow so fast that course of a stream is diverted?" Or putting it in another way, "what is the maximum slip rate that the stream can sustain before being diverted?"

Future developments of the above illustrated approach will help explore fault characteristics by providing a strategy in determining long-term (10-100 ky) slip rates and in evaluating the ratio between the rate of slip at depth on blind faults and the rate of regional uplift. As the spectrum of capabilities of computer tools, such as those presented here, will widen and improve the work of the tectonic geomorphologist will inevitably change. These tools can strongly help characterise seismogenic faults especially in areas where classical geological methods are difficult to apply, perhaps one of the main goal of the project SAFE.

2. Software and algorithms

2.1. The ARD program

ARD 1.0 (Anomalous River Drainage), is a tool designed to help the user detect river anomalies. The basic idea of this program is that river flow follows the route of steepest descent. Wherever this does not occur a river anomaly is detected. To do so the program computes two vectors: the first represents the actual flow direction of the river, and the second represents the steepest direction of the surrounding topography. Both river and topography points are sampled within search radii given by the analyst to give the possibility of detecting anomalies at different length scales. An ideal behaviour of the river will lead to a perfect match of the two directions. If the two vectors differ significantly the program warns the user that a possible river anomaly was detected. The interpretation of the origin of the mismatch between the two vectors is left to the analyst. More importantly, the definition of the amount of angular separation between the two vectors required to identify an anomalous behaviour, whatever its origin, relies on the analyst's expertise. No automatic selection of anomalous river reaches is provided by the program. The program only provides the analyst with an objectively calculated set of information.

System requirements: PC platform, Windows 98, or later, operating system, memory and mass storage availability depending on size of input data.

The code is written in FORTRAN and is designed as a console application that runs without any user-driven event. This means that while the program runs in a DOS-like window no Graphic User Interface (GUI) will pop up and no command-line action will be requested. However, the program will inform the user about the status of the current action as a percent of completed task. The only way to interact with the program is through the specifications given in the input files. The structure of the algorithm is very simple and can be summarised as three main steps: (1) loading of input data by reading three input files; (2) accomplishment of four computational tasks; (3) storing of results by saving several output files in the mass storage device.

INPUT DATA: Parameters of analysis: The program at start up reads an ASCII file that contains the information needed to perform the analysis. The name of this file must be `input.txt`. Specifically, the user has to provide (1) the name of the file that contains the DEM data; (2) the name of the file that contains the river course data; (3) the search radius, in meter, to be used in calculating the river vector; and (4) the search radius, in meter, to be used in calculating the topography vector. The latter two may also be the same, however, it is recommended that the topography search radius be two



or three times as great as the river search radius. The above information has to be supplied according to the following format, where the exclamation mark denotes comment lines.

```
! Name of DEM file to be read
roglio100.txt
! Name of river file to be read
rogliocourse.txt
! River course search radius (m)
2000.
! Topography search radius (m)
5000.
```

Digital Elevation Model. The program uses as input data a Digital Elevation Model (DEM) with square cells. Size of cells must be in meters. Geographic coordinate system has also to be expressed in meters. The DEM has to be supplied as an ASCII file formatted according to the following sample scheme:

```
ncols 300
nrows 300
xllcorner 330000
yllcorner 4740000
cellsize 100
NODATA_value -9999
Z1,1 Z1,2 ... Z1,ncols
Z2,1 Z2,2 ... Z2,ncols
...
Znrows,1 Znrows,2 ... Znrows,ncols
```

where the first six lines (the header) contains general information about the DEM and the subsequent lines (the gridded data) contains the actual elevation of the ground surface. From top to bottom symbols are as follows: `ncols` and `nrows` are the number of columns and rows of the grid respectively; `xllcorner` and `yllcorner` are the Easting and Northing of the lower left corner of the grid in meters; `cellsize` is the side length of the grid cells in meters; and `NODATA_value` is a dummy value to identify possible cells that contains NaN (Not a Number) values. $Z_{1,1}$ through $Z_{nrows,ncols}$ are the actual elevations stored in a grid with the column number increasing rightward and row number increasing downward. Elevation can be stored either as integer or floating-point values.

River path coordinates. The program uses as input data a file containing the course of the river to analyse in the form of coordinate pairs. Coordinates have to be given in the same system of the DEM. Theoretically, the program needs only to be instructed upon the start- and end-points of the river course. Practically, it is better to feed the program with a larger number of river points to ensure a better reconstruction of the river course. Although, the program has the capability of reconstructing the

drainage network of the whole area on the basis of the topographic information given through the DEM, it is important to keep in mind that drainage routing algorithms tend to fail in low relief topography. ARD is not an exception. To prevent errors and, especially, to reduce the user trials in reconstructing the route of the analysed river the ARD program uses this information to check the drainage route while running. There is no predefined limit to the number of points. The data have to be supplied according to the following example.

```
566117.4 5043844.44
566117.4 5043124.02
566213.46 5042403.61
...
Xn Yn
```

CALCULATIONS: Task 1: Pre-processing. The very first action of the ARD program is to execute a series of subroutines that search the most common errors that are usually found in DEMs and tries to correct them. Two common errors in DEMs are the so-called "pits" and "plateaus". A pit occurs where a cell has a lower elevation than its eight neighbouring cells. A plateau occurs where a cell has exactly the same elevation as its eight neighbouring cells. These two cases usually occur when DEM data are stored as integer values - a common practice for saving disk space. Although in some cases pits and plateaus may represent true geomorphic features, they are not expected to occur within river valleys. However, their removal is done by modifying the intervening elevation by a quantity that is much smaller than the DEM formal accuracy (e.g. 1 m for a DEM stored as integer values in meters) so that the original data are not significantly modified. Standard geomorphic properties such as aspect and slope of each DEM cell is calculated and stored in cache for later use.

Task 2: Search of river path vectors. Following the approximate river path provided by the user, the program finds a more detailed river course by applying a drainage routing algorithm. Each draining cell drains toward every lower cell among its eight neighbours. If no lower cells are found the draining cell drains only toward the cell found in the direction of maximum steepness calculated during pre-processing. If not all the pits and plateaus were removed in the pre-processing this algorithm may halt at some point. In this case it searches the nearest available draining cell provided in the input file and carries on.

A vector that represent the main direction of the river path at every draining cell is then calculated through Principal Component Analysis (PCA). PCA is applied at clusters of river cells made by grouping together all the draining cells that are found within a search radius having the length specified in the input file. The cluster centroid is arbitrarily put in coincidence with the locus of the object cell. The

two Principal Components (PCs) of each cluster are identified as the two eigenvectors and eigenvalues of the variance-covariance matrix of the cluster coordinates with respect to the cluster centroid. The eigenvector with the largest eigenvalue is chosen as the main direction of the river at the given point. If the ratio between the two eigenvalues exceeds a lower default limit the program warns that the search length is too short and, thus, the results will be unreliable. Each unit vector is applied at each cluster centroid. Its direction is given in degrees in the range $-90 - 90^\circ$, rounded off at the nearest integer value, clockwise from North.

Task 3: Search of topography vectors. The program first retrieves all the elevations of the topography cells falling within a search radius having the length specified in the input file and centred at every drainage cell. It then searches the orientation of the ideal plane that best fit these data. DEM cells with local relief exceeding a lower default limit are discarded before performing the fit. This cautionary rule is followed to take into account the undesired effects of scattered unusual elevations of piedmonts into the calculations of the slope direction. An additional cautionary rule is followed by calculating the correlation coefficient of the best-fit plane and comparing it with a default value. Low correlation coefficients mean that the ground surface surrounding the river reach may be too rough to be approximated with a planar surface and that the comparison between such plane and the direction of river flow may be meaningless. The dip direction of each best-fit plane is taken as the topography vector and is applied at the central cell. This direction is given in degrees in the range $-90 - 90^\circ$, rounded off at the nearest integer value, clockwise from North.

Task 4: Comparison of river and topography vectors. Provided that all the unsuitable vectors were correctly discarded and that a significant amount of suitable vectors were found, the horizontal angular separation between each river and topography vector is calculated. Its value is given in degrees, rounded off at the nearest integer value.

OUTPUT: The program writes a set of four ASCII files while running. The first file is named `log.txt`, and records all the actions done while running. Information saved in the log file includes significant values of the input files read, critical values of the errors found in the DEM, summary of the calculated morphometric properties, and a summary of the reconstructed drainage network. The second file is an updated version of the DEM as modified through the removal of pits and plateaus. The name of the file is `chkdem###.txt`, where the symbol "###" stands for a numeral that identifies the iterations required to achieve that result. This file can be used to estimate the difference between the original DEM data and those actually used by the program. The third file, named `drgnet.txt`, is a map of the reconstructed drainage network. It has the same format of the DEM file. The cell values can be 0 or 1, where 1 means that that cell is a draining cell. The fourth file, named `vectortable.txt`, contains the results of the analysis in tabular form. The table has the

following six columns: (1) ordinal number of the vector; (2 and 3) Easting and Northing, respectively, of the point where the vectors are applied, in meters in the same coordinate system implicit in the given DEM header; (4) dip direction of the river vector, in degrees CW from North, in the range -90-90°; (5) dip direction of the topography vector, in degrees CW from North, in the range -90-90°; (6) angular separation between the river and topography vectors, in degrees.

SAMPLE FILES: The area of the River Oglio is chosen among the already known drainage anomalies of the Po Plain, illustrated by Burrato et al. 2003, as an evident example of the functionalities of the ARD program. The River Oglio flows almost North-South from the Alpine piedmont toward the River Po, which flows almost West-East. Before joining the River Po, the River Oglio makes a rather sharp turn to the East (figure 1a). This example demonstrate that this turn of the River Oglio is not in accordance with its surrounding topography because there is a significant divergence between the river flow direction and the direction of the maximum steepness of the surrounding topography (figure 1b and 1c). The three close-ups of figure 2 show more clearly the initial accordance of the vectors in the northern portion of the river course, the point where the two vectors begin to diverge strongly, and that the anomalous behaviour persists over a long portion of the southern reach of the river. Notice that the angular separation between vectors in the lower reach is almost 90°. The program, of course, does not tell anything about the true reason that drives the turn, which remains a matter of interpretation left to the analyst.

The following files, stored in the compressed archive "ARDdemo.zip", are enclosed as a demonstration of the program functionalities and to provide the user with a facsimile that can be used to prepare the input files.

file name	description	file type
ARD.exe	the ARD program	executable
input.txt	file containing the names of the input data files and the parameters that will be used by the program	input
rogliol00.txt	DEM of the sample area	input
rogliocourse.txt	coordinates of the sample river course	input
log.txt	log file of the operations performed by ARD	output
chkdem002.txt	DEM of the sample area as modified for calculation requirements, elevations are stored as floating-point values	output
drgnet.txt	drainage course of the sample river in matrix shape, draining cells are set to 1, all the others are set to 0	output
vectortable.txt	results of the analysis including coordinate pairs of all drainage points, orientation of vectors and angular separation	output

2.2. The FaultStudio program

FaultStudio 1.0, is a tool designed to devise self-consistent earthquake faults, manipulate their parameters and store values to a database. It has also a function to model the surface displacement produced by a single displacement event on a fault.

An intuitive Graphic User Interface (GUI) allows the user to easily interact with the program and get the best out of its functionalities. The GUI is very friendly and self-explaining and its action controls are named using the most common geologic/tectonic jargon. This means that it is assumed that the user is already familiar with terms like "strike", "dip", "rake" and so on. The meaning of this terminology will not be explained here and the interested reader is invited to consult tectonic manuals to find definitions of these terms.

The program runs under MapInfo v. 6.5 or later. Many of its functionalities are provided directly from MapInfo. In this report it is assumed that the reader is already familiar with the MapInfo software and its jargon. The entire program includes a suite of files and folders, whose names and structure are shown in the following table, that are stored in the compressed archive "FaultStudio.zip".

file name	location and description	file type
FaultStudio10.mbx	The FaultStudio program. Is located in the FaultStudio folder.	executable
FaultScenario.exe	The FaultScenario program. Is a FORTRAN program that makes the calculations of modelling displacement. Is located in the FaultStudio folder.	executable
input	The folder where the files used in the modelling procedure will be saved.	folder
output	The folder where the files of the results of the modelling procedure will be saved.	folder

The files listed in the following table are event-dependent. The first is created automatically at start up, the other are created on demand during a FaultStudio session depending on the event that is generated by the user. None of them need to exist when FaultStudio is first launched.

file name	location and description	file type
FaultFile.tab (map, id and dat)	File set, in the MapInfo table format, that contains the record of the FaultStudio database. Need not to exist when the program is launched. Will be automatically created at start up and saved in the FaultStudio folder. The database will contain no records until a new fault is added or an import operation is done.	MapInfo table
Fault2Model.txt	Text file containing the parameters of the fault(s) that will be	input

	used in the displacement modelling. It is created and saved in the input folder when the user starts the modelling procedure.	
mapfile.txt	Text file containing information about the grid over which the model is calculated. It is created and saved in the input folder when the user starts the modelling procedure.	input
Src###CC.xxx	Set of files containing the results of the displacement modelling. Its name is generated dynamically. Src is short for source; ### is the number of the fault as stored in the database; CC is a two-character code that identifies the component of displacement; xxx is the extension that denotes the type of the file. The results in grid format are stored as ASCII files with the txt extension whereas those in contour format are stored in the MapInfo table format. They are created and saved in the output folder when a fault modelling procedure is done.	output
log.txt	Text file containing a log of the tasks performed by the modelling procedure. It is created and saved in the output folder when a fault modelling procedure is done.	output
BorderMap.tab BorderTXT.tab (map, id and dat)	They are created and saved in the FaultStudio folder when a create map border event is prompted.	output

At start-up the program does the following actions (Figure 3): (1) adds a new down-drop menu named "FaultStudio" in the MapInfo menu bar; (2) opens a MapInfo table named "Fault-File.tab" or creates it if the file does not exist in the application folder; (3) opens a new map window; (4) opens a new browser window; (5) opens a message window.

The down-drop menu includes the following items and sub-items (indicated between square brackets):

```

Load background map(s)...
Create map border...
New Fault...
Modify Fault >>      [Adjust...;
                      Duplicate...;
                      Delete...;
                      Delete All]
Save and Pack Fault File
Import >>             [from DISS 2.0;
                      from ASCII File...]
Export >>             [to DISS 2.0;
                      to ASCII File...]
Fault modelling >>    [Setting Model Preferences...;
                      Calculate Displacement...;

```

View Result...]
About FaultStudio...
Exit FaultStudio

The new map and new browser windows will show the objects (i.e. the fault symbols) recorded in the file `FaultFile.tab` that constitutes the database of the program. If the file has just been created and thus is empty, the user is warned about this occurrence through a dialog window.

The message window will inform the user about the current events prompted by the user.

The "New Fault" dialog window (figure 4) provides the user with a tool to insert a new record (i.e. a fault) in the database of the program (the file `"FaultFile.tab"`). This window has two frames: the left-hand frame includes a series of controls that allows the user to enter the main parameters of the new fault; the right-hand frame shows a summary of all fault parameters, including those calculated by the program. The "Update Summary" button updates the values of the parameters shown in the summary frame. The "Map" button causes the fault to show in the map window and its parameters to show in the browser window. The map window zooms on the fault area at the appropriate scale automatically. The "Cancel" button dismisses the "New Fault" dialog without taking any further action. This means also that any information already entered is lost.

The "Modify Fault" dialog window (figure 5) provides the user with a tool to modify a record (i.e. a fault) in the database of the program (the file `"FaultFile.tab"`). Similarly to the "New Fault" dialog window, this window has two frames. The upper frame is subdivided into several sub-frames where a single property of the record can be modified. Although more than one property can be modified at a time, multiple modifications can be difficult to follow and thus this practice is not encouraged. The "Apply" button updates the entire fault record and the map window, the browser window, and the lower frame of the dialog window are updated on the fly. The Lower frame of the dialog shows a summary of the fault properties. The "Discard" button discards all the current modifications, however the pending changes remains committed to memory. The "Cancel" button discards the current modifications and dismisses the dialog. The "Done" button saves the current modifications in the record of the database and dismisses the dialog.

The "Fault Modelling" command is composed by three different sub-commands that identify a three-step procedure through which the user can obtain a model of the surface displacement of due to a single event of slip on the selected fault. The model is calculated using the approach defined by Okada (1985). The sub-commands are initially disabled. The "Setting Model Preferences..." command is enabled when a fault is selected. This command causes the "Set Preferences" dialog window (figure 6) to pop up. Through this window the user first define the size, shape, and density of the grid over which the calculations will be made and selects which component of displacement to calculate. After dis-

missing this window, the "Calculate Displacement..." command is enabled. It launches an external program, the "FaultScenario.exe" FORTRAN code, that runs in a console window and performs all the necessary calculations. The "View Result..." command is now enabled and opens a dialog window through which the user can choose the style and colour of the contour lines of the displacement map and select/unselect the option of having a border around the contour map. The display of the contour map (figure 7) will have the size and shape defined through the "Set Preferences" dialog window.

The rest of the FaultStudio commands performs very simple actions that provide the user with very common utilities and thus will not be illustrated here. Only notice that the import/export utilities allows the user to convert the content of the `FaultFile.tab` to and from the format of the DISS 2.0 (Valensise and Pantosti, 2001) and a tabulated ASCII format.

2.3. The LEM program

LEM 1.0 (Landscape Evolution Model), is a tool designed to go further into the modelling of fault displacement, allowing the user to simulate the landscape evolution under various conditions of tectonic forcing and to test the reliability of the tectonic-geomorphologist's conjectures. The basic idea of this program is to simulate the modifications of the ground surface over a specified time interval and compare the results of the simulation with the observations of the real landscape.

System requirements: PC platform, Windows 98, or later, operating system, memory and mass storage availability depending on size of input data.

The code is written in FORTRAN and is designed as a console application that runs without any user-driven event. This means that while the program runs in a DOS-like window no GUI will pop up and no command-line action will be requested. However, the program will inform the user about the status of the current action as a percent of completed task. The only way to interact with the program is through the specifications given in the input files.

The structure of the algorithm (figure 8) is rather simple and flexible. It includes the following main steps. (1) Loading of input data by reading the input files. (2) Allocation of necessary memory and initialisation of variables. (3) Accomplishment of the computational tasks within the given temporal framework. This includes the updating of several parameters (run-time dependencies) and the on/off switching of the appropriate modelling action. The latter is basically the calculation of the elevation of every cell in the model lattice at every time increment by summing contributions from all the active processes. (4) Storing of results by saving several output files in the mass storage device.

INPUT DATA: Parameters of analysis: The program at start up reads an ASCII file that contains the information needed to perform the analysis. The name of this file must be `input.txt`. Such information has to be supplied according to the following format, where the exclamation mark denotes comment lines.

```
! toggles: ut, fd, sl, dr, df
1 1 0 1 1
! grid shape and size
0.0 0.0 1.0 1.0 50 100
! temporal cycle
0 100000 100 20000
! regional uplift parameters
180.0 0.000002 0.0
! fault geometry parameters
1 1 15.0 80.0 90.0 1 7.0 30.0 170 34 0.0 1000.0 0.0 20.0 12.0
! fault recurrence parameters
500.0 0.0 100000.0
! spring parameters
25.0 70.0 -0.01
! end of input file
```

The sequence of toggles determine which routine has to be activated in the model calculations. They assume the value 0 if the routine has to be switched off and 1 if the routine has to be switched on. They enable/disable the processes of uplift-tilt, fault displacement, slope erosion, stream channel erosion, and diffusion respectively. Grid shape and size parameters define the space over which the landscape evolution is modelled. Their values represent, respectively, the grid origin coordinate on the X axis in km; the grid origin coordinate on the Y axis in km; the cell size along the X axis in km; the cell size along the Y axis in km; number of cells along the X axis; number of cells along the Y axis. The temporal cycle parameters control the clock of the model time. The sequence of values represents beginning, end, increment, and snapshot respectively. They are all expressed in years. Snapshot time determines when the current status of the model has to be stored in a map file. Regional uplift/tilt parameters define the dip direction of tilt, expressed in degrees clockwise from North (implicitly aligned with the Y axis), rate of tilt in degrees per year, vertical component of uniform uplift in millimetres per year, respectively. Fault geometry parameters are as follows: fault segment ordinal number, fault patch ordinal number, X coordinate of bottom-left corner of fault patch in kilometres, Y coordinate of bottom-left corner of fault patch in kilometres, strike in degrees clockwise from North (Y axis), toggle that assumes the value 0 for a point source and 1 for an extended rectangular source, depth of the fault bottom edge in kilometres, dip angle in degrees, Lamé's constant λ in Pa, Lamé's constant μ in Pa, horizontal (i.e. along strike) component of slip in millimetres, vertical (i.e. down dip) component of slip in millimetres, tensile component of slip in millimetres, length of fault patch in kilometres, width

(down dip) of fault patch in kilometres. Fault recurrence parameters are as follows: recurrence interval between successive slip events in years, inception time in years, end time in years. Spring parameters define the location of known stream heads expressed as distance along the X and Y axes, in kilometres, and the erosion power of the stream defined as the lowering rate of the topographic surface at the stream head expressed in millimetres per year.

THE ALGORITHM: A cellular automaton simulates the landscape evolution according to two sets of rules: 1) the tectonic rule set which controls crustal (regional) uplift/tilting/subsidence and fault displacement; 2) the geomorphic rule set which controls surface degradation as a diffusive process and fluvial erosion-transport-deposition. The model space is a 2D lattice with uniform cell distribution. The model time proceeds with regular finite increments. Regional component of tectonic movement enters the model as a kinematic value. It is assumed that the value is known from tectonic studies. Local tectonic displacement due to faulting is modelled after the Okada (1985) formulations.

$$u_i = \frac{1}{F} \iint_{\Sigma} \Delta u_j \left[\lambda \delta_{jk} \frac{\partial u_i^n}{\partial \xi_n} + \mu \left(\frac{\partial u_i^j}{\partial \xi_k} + \frac{\partial u_i^k}{\partial \xi_j} \right) \right] \nu_k d\Sigma$$

Input values includes geometry, size and amount of slip on a finite rectangular fault embedded in an elastic half-space. Surface degradation as a function of local curvature is modelled through the well known diffusion equation in two dimensions which predicts that the higher the topographic gradient, the faster the erosion/deposition processes.

$$\frac{\partial z}{\partial t} = \kappa \left(\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right)$$

Fluvial erosion is given by the following formulation introduced by Howard et al. (1994)

$$\frac{\partial z}{\partial t} = kA^m S^n$$

where A is drainage area and S is slope. Fluvial deposition is not implemented.

The application of the above mentioned geomorphic and tectonic rules requires that several properties of the ground surface and of the faults be known at every incremental time step. A set of sub-procedures accomplishes this task. They are included in the program scheme (figure 8) into a single block named "run-dependencies".

To simulate the development of the drainage network the first problem to solve is the initiation of channels. This is a little trickier problem than basic drainage routing because it deals with the question of where and how in the model area a given cell will start behaving as a drainage channel rather than a slope or plain. Most of the landscape evolution models solve this problem by assigning the rank of channel to any cell where the calculated stream power exceeds the threshold for bed load transport. Although this solution simulates well enough the conditions of arid and semi-arid regions, it fall short in temperate environments, as most of the European land. In fact, the stream-power threshold neglects the possible contribution of underground water reservoirs that feed the drainage wherever they come out to the ground surface, via fracture or porous rocks. To take into account this contribution stream heads can be positioned in the model at any point where a perennial spring is thought to occur. In the LEM program this problem is dealt with by positioning stream heads at known place and wherever stream power exceeds the threshold for bed load transport. The amount of water discharged by springs has also to be known. As the location of stream heads is known the pattern and properties of the drainage network can be determined by adopting an algorithm of drainage routing and upslope area estimation. This program adopts a D8 algorithm that is one in which any drainage cell drains toward the neighbouring cell located along the direction of steepest descent (Tarboton, 1997). The rules controlling the elevation modifications within the drainage cells can then be applied provided that aspect and slope as the first derivative of elevation in the previous step of those cell is already know.

The simulation of surface degradation outside the drainage network requires that also the local curvature be determined as the second derivative of elevation.

The simulation of the fault behaviour is instead accomplished by applying a recurrence model of fault displacement based on a simple set of parameters. The recurrence model (figure 9) is described by the curve

$$D = \delta(mT^n - \rho)$$

where D is displacement in millimetres, T is the time interval between successive seismic release in years, n is a positive, finite value that describes the curvature of the time vs. displacement curve, m is the slope of the curve, δ is a switch that determines whether the pattern of faulting through time is accelerating or decelerating, and ρ is interseismic displacement in millimetres evaluated as percentage of the seismic slip D. If T is assigned the value 0 the curve is continuous and simulates the stable sliding behaviour. Any other positive value of T will result in a step-like geometry that simulates a stick-slip behaviour. If n is assigned the value 1 this equation describes a straight line, i.e. a strictly periodic earthquake recurrence. Any other positive n describes an exponential curve, that is to say that displacement varies through time. The switch δ simply operates a double rotation of the curve, first about

an horizontal axis and then about a vertical axis, to simulate accelerating and decelerating pattern. The percentage of interseismic slip ρ determines the amount of slip that is released between two successive seismic events. Although this function, in its simplicity, combined with a set of faults with different time of inception and end can simulate a practically indefinite gamut of behaviours, the user is warned about indulging in its use to not loose control of how faulting affects landscape modifications.

Future developments of the algorithm can be envisaged as the improvement of both rule sets. The modelling will especially benefit from a more robust estimation of the hill-slope and river erosion/deposition by including factors controlling the production of regolith depending on lithology, a control on sediment budgeting during transport, and sea/base level fluctuation along with climate forcing.

OUTPUT: The program writes a set of ASCII files while running. One file is named `log.txt`, and records all the actions done while running. Information saved in the log file includes significant values of the input files read and of the completed tasks. The other files are gridded values of the model elevation and of the model geomorphic properties at the specified time intervals, i.e. the so called snapshots.

SAMPLE FILES: Two experiments using the LEM program will be illustrated below.

Model #1: The purpose of this experiment is to analyse how efficiently ground surface warping due to fault displacement affects the course of a stream in presence/absence of tectonic regional uplift and subsidence. Model #1 is a very simple experiment which incorporates tectonic regional uplift, fault displacement and drainage routing. It does not take into account any contribution of landscape development from erosion/deposition processes. Model #1 covers an area of 50 x 50 km subdivided into 1 km cells. Starting conditions are as follows: 1) N-S planar regional slope of 10-3 degrees (0.018 m/km); 2) E-W striking blind thrust fault, dipping 30° to the North, located near the southern edge of the model area; 3) two stream heads located near the northern edge of the model area (figure 10). Notice that at starting conditions the two streams already have a rectilinear flow from North to South according to the direction of maximum steepness. The routes followed by the two streams are investigated under two different circumstances:

1. local warping due to sustained faulting at a slip rate of 0.5 mm/y in the absence of regional tectonic tilting;
2. same local warping as in a) combined with regional tectonic tilting of 10-6 deg/y about an E-W axis coincident with the southern edge of the model area.

Figure 11 shows the results of the two model cases at three time steps of 2, 6, and 10 ky respectively. Without regional tectonic tilting (three upper diagrams in figure 2) the two streams are first

diverged from their rectilinear N-S path by the anticline they encounter along their courses (2 ky). As time passes (6 ky) a depression (syncline) develops on the back-limb of the growing anticline which attracts the stream flow that converges to the lowermost point of the depression. At the final stage (10 ky) the streams are definitely ponded in the depression while their point of diversion was shifted northward. Including regional tectonic tilting (three lower diagrams in figure 2) the two streams are first diverged from their rectilinear N-S path by the anticline they encounter along their courses (2 ky). As time passes (6 ky) the streams are progressively diverged toward the eastern and western sides of the model area. At the final stage (10 ky) the streams are even more laterally shifted. Apparently the point where the streams are being deviated remains stable. It is worth noticing that regional tectonic tilting prevents the syncline from forming and the inward diversion of the stream flow.

Model #2: The purpose of this experiment is to analyse the change in shape of the ground surface due to the combined effects of regional tectonic tilting, local warping due to fault displacement, linear incision due to stream erosion and sediment diffusion (weathering) due to slope changes. Model #2 incorporates both tectonic and, although simple, geomorphic rules applied to an area of 100 x 50 km subdivided into 1 km cells. Starting conditions are as follows: 1) regional slope having different steepness from North to South to resemble a regional divide (at 80 km from southern edge of model area), a 50 km long steep planar slope, and a foothill slope break (at 30 km from southern edge of model area) connecting to a 30 km long gentle planar slope of; 2) E-W striking blind thrust fault, dipping 30° to the North, located near the southern edge of the model area; 3) one stream head located near the regional divide (figure 12) at mid width of model area. Notice that at starting conditions the stream already has a rectilinear flow from North to South according to the direction of maximum steepness. The model simulates the landscape evolution by predicting the formation of an incised valley with shoulder height varying as both topography and catchments vary. The vertical incision is proportional to the stream power at each stream-cell location. Stream power varies through space and time according to local topographic warping due to sustained faulting at a slip rate of 0.5 mm/y combined with regional tectonic tilting of 10-6 deg/y around an E-W axis coincident with the southern edge of the model area. Figure 13 shows the results of the model after 40 ky of model time has passed. Several realistically simulated topographic features can be observed.

1. The sharp-edged watershed has been substantially smoothed out by material removal due to diffusion.
2. Similarly, the foothill slope break has been blanketed by sediments coming from upslope due to the same diffusion process.

3. An incised valley has developed along the predicted stream course (steepest descent route) with shoulder height increasing downstream as drainage area increases and slope remains constant.

The shoulder height decreases where the stream enters the foothill plain, even though drainage area still increases, because of abrupt slope fall. The stream valley shoulder heightens locally where slope increases along the anticline fore-limb and decreases again at the anticline outskirts. Local ground warping due to faulting is apparently not fast enough to divert the course of the stream which crosses the anticline axis. As the anticline grows, however, the stream is expected to be diverted and its valley across the anticline axis is abandoned thereby forming a wind-gap.

The following files, stored in the compressed archive "LEMdemo.zip", are enclosed as a demonstration of the program functionalities. They represent the example described in the Model #2 experiment.

file name	description	file type
LEM.exe	The LEM program.	executable
input.txt	File containing the parameters that will be used by the program.	input
log.txt	Log file of the operations performed by LEM.	output
##\$out.grd	Set of 9 files containing gridded elevation values or geomorphic properties of the model surface after 100 ky of model time in the Surfer Grid ASCII format. The filename is coded as follows: ## is a two-digit ordinal representing the snapshot number, \$ is a single-digit ordinal representing the content of the file, 0 is the topographic elevation, 2 is local slope, 3 is local aspect, 4 is local curvature along the X axis, 5 is local curvature along the Y axis, 6 is drainage network, 7 is upslope drainage area, 8 is catchment extension, and 9 is amount of diffusion.	output

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Figure captions

Figure 1. Course of the River Oglio reconstructed on the basis of the DEM data and the approximate river course data (left). Vectors of the river clusters (middle) as identified by using a search radius of 2000 m (blue search circle). Vectors of the topography surrounding each river cluster (right) as identified by using a search radius of 5000 m (red search circle).

Figure 2. Three close-ups of the river vectors (blue lines) and topography vectors (red lines) in three different sectors of the River Oglio course (vector length is arbitrary). Notice the perfect agreement between the river course and the topography in the northern sector (uppermost panel), the significant divergence between topography and river course in the middle that indicate the beginning of an anomalous behaviour (central panel), and the consistency of the divergence in the southern portion that indicate the anomaly is over 5 km long (lowermost panel).

Figure 3. The FaultStudio program at start up. Notice the main menu, already dropped down, added on the right end of the MapInfo menu bar. The map, browser, and message windows are also open. The topography displayed in the map window has been added using the "Load background map(s)" command from the main drop-down menu.

Figure 4. The "New Fault" dialog window displayed on the right of the map window. After having entered the parameters the a new object is added to both the map and the browser window. The map window will also automatically zoom on the new fault.

Figure 5. The "Modify Fault" dialog window displayed on the right of the map window. The apply button refreshes the map window on the fly and causes the modifications to display automatically. This functionality is especially useful to adjust the location and geometry of a fault before any map that displays geological or geophysical information.

Figure 6. The "Set Preferences" dialog window allows the user to enter several parameters that will be used to model the surface displacement due to an event of fault slip.

Figure 7. Model of the surface displacement due to a fault. The map window shows a contour display of the vertical displacement. The map border and title are added on demand through a dialog window that appears after the model calculations are completed. The message window, on the right-hand side, show a log of the latest actions taken by the program.

Figure 8. Schematic representation of the LEM algorithm. Blocks on the left-hand side performs the initialisation tasks. The simulation of the landscape modifications over time are represented in the centre of the scheme. The net surface modification is calculated as the sum of all contributions from the various processes. SL: slope processes; DR: drainage processes; FD: fault displacement; UT: regional uplift or tilt. Notice the block "run dependencies" that includes a set of ancillary routines that update all the model properties during run-time at each time-step increment. Handling of output actions are represented on the right-hand side of the scheme. Snapshots of the model evolution are taken at regular intervals by printing to files the model surface properties in grid format.

Figure 9. Recurrence model of a seismogenic fault expressed as amount of total displacement vs. time (arbitrary units). Bluish curves represent accelerating patterns. Reddish curves represent decelerating patterns. Behaviour varies also between stick-slip (step-like curves) and stable sliding (continuous curves). Step-like curves with inclined trends simulates interseismic stable sliding.

Figure 10. Model #1: model settings at starting conditions in plan view. Arrows indicate stream flow according to regional slope. Elevation and slope have realistic values but do not correspond to any particular real place.

Figure 11. Model #1: model snapshots at 2, 6, and 10 ky in plan view. The three upper diagrams show how the stream courses are progressively diverged toward the lowermost point of the depression developed on the back-limb of a growing anticline. The lower three diagrams show how the presence of tectonic regional tilting prevent



the formation of the syncline and the stream courses are progressively shifted away from the anticline. Contour interval is 0.2 m and is the same in all diagrams.

Figure 12. Model #2: model settings in orthoscopic view at starting conditions. Fault maximum and minimum depths are not to scale. Elevation and slope values resemble those of the real topography of the northern Apennines facing the Po Plain, orientation does not.

Figure 13. Model #2: model snapshot in orthoscopic view after 40 ky of model time. Several realistic-looking geomorphic features have formed under the combined interactions of tectonic and geomorphic processes. At this stage of the simulation the stream course still crosses the anticline bump, however, an incipient wind-gap may be envisaged at the fore-limb due to expected progressive abandonment as back-limb steepens.

Figure 1

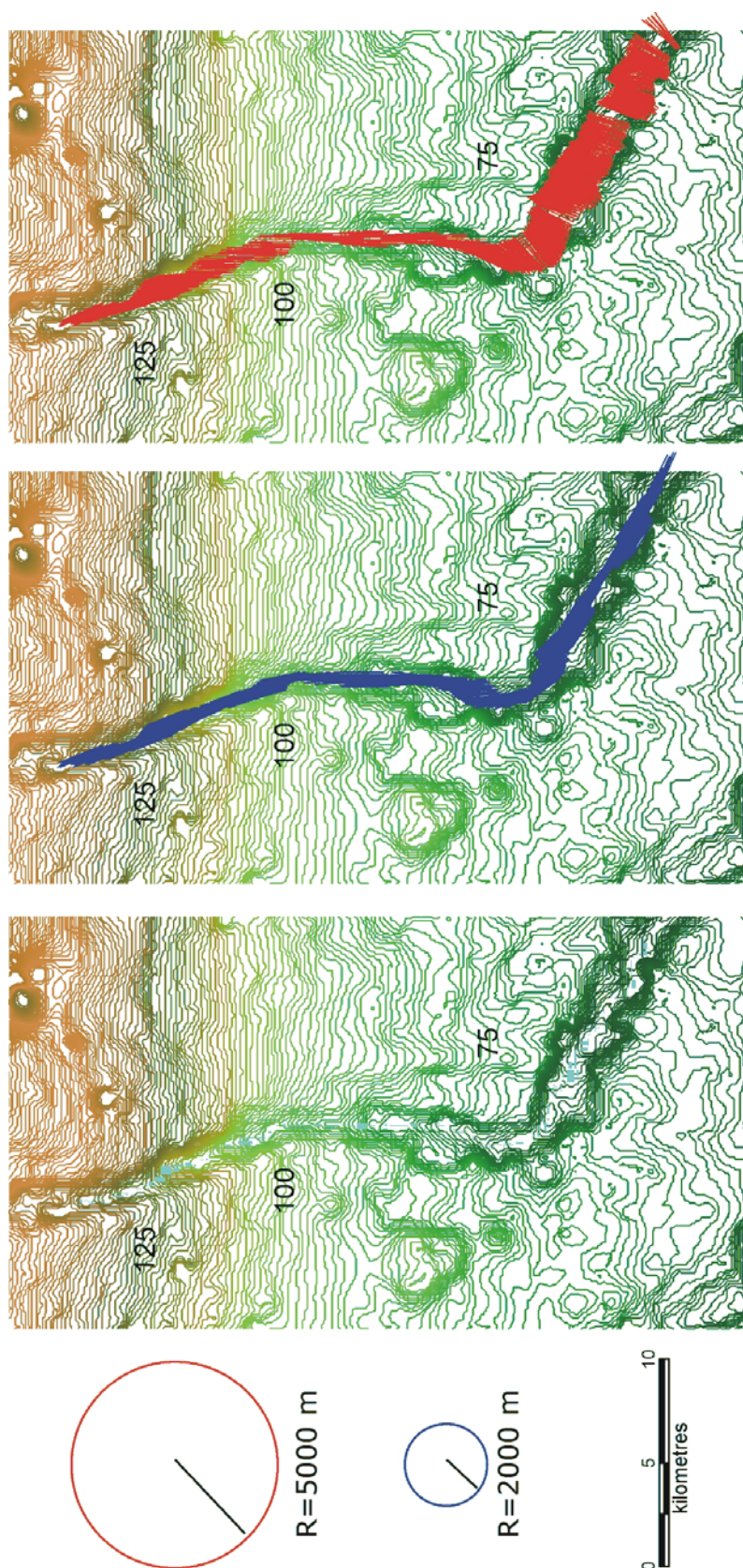


Figure 2

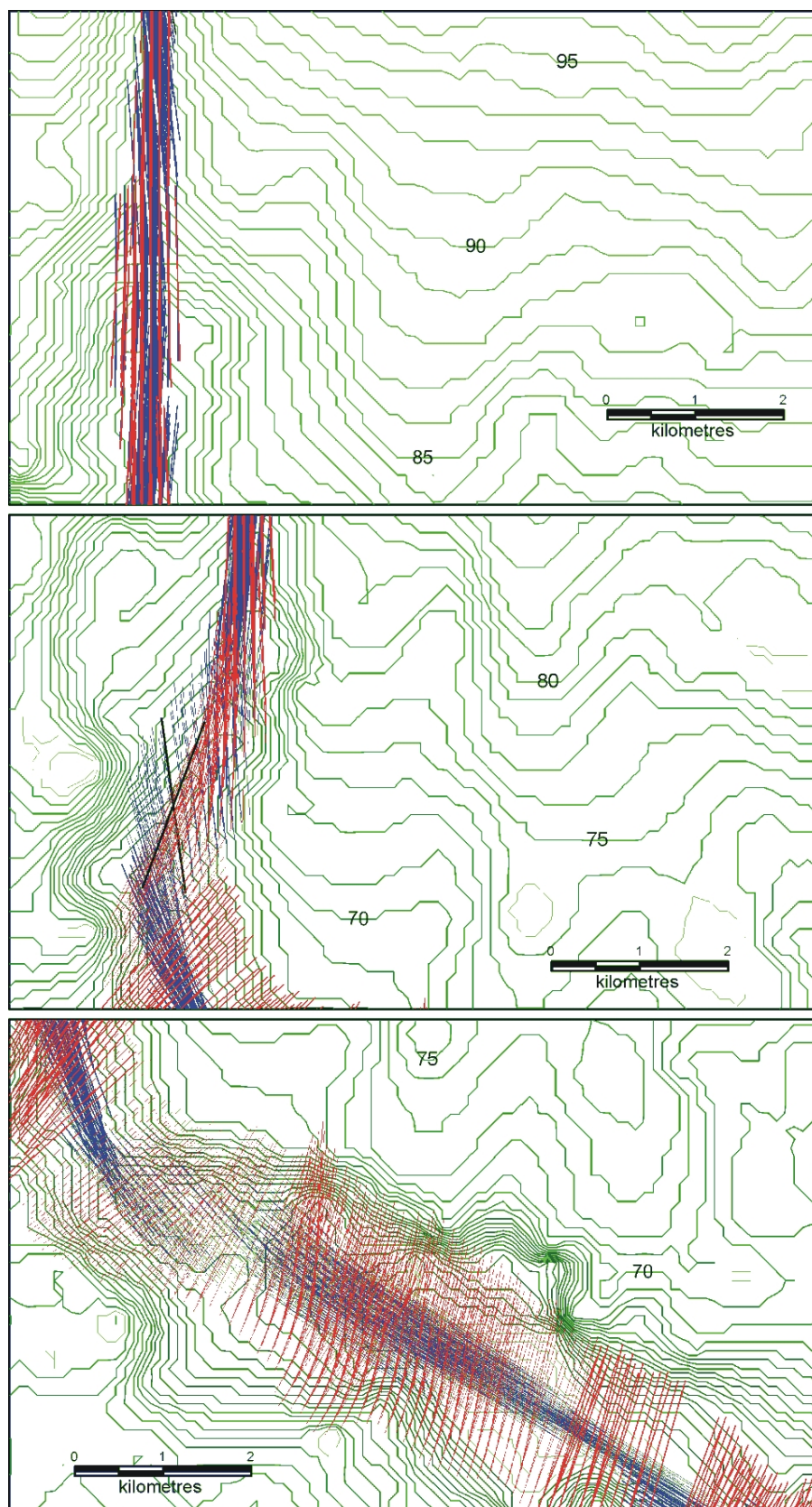


Figure 3

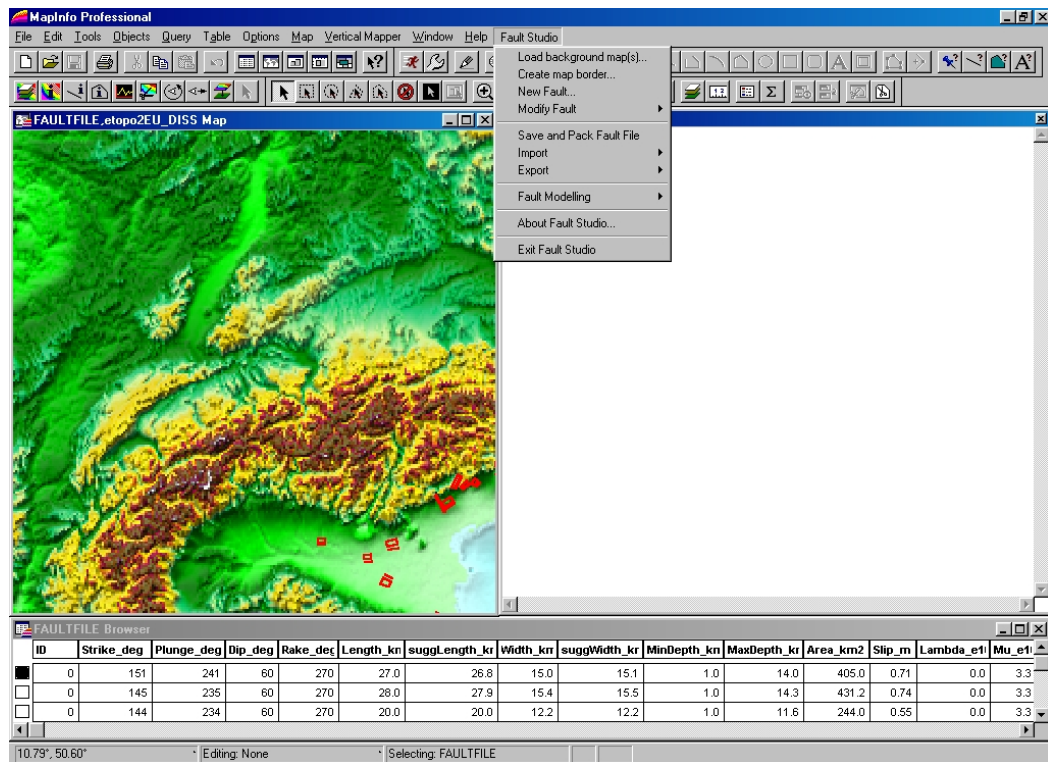


Figure 4

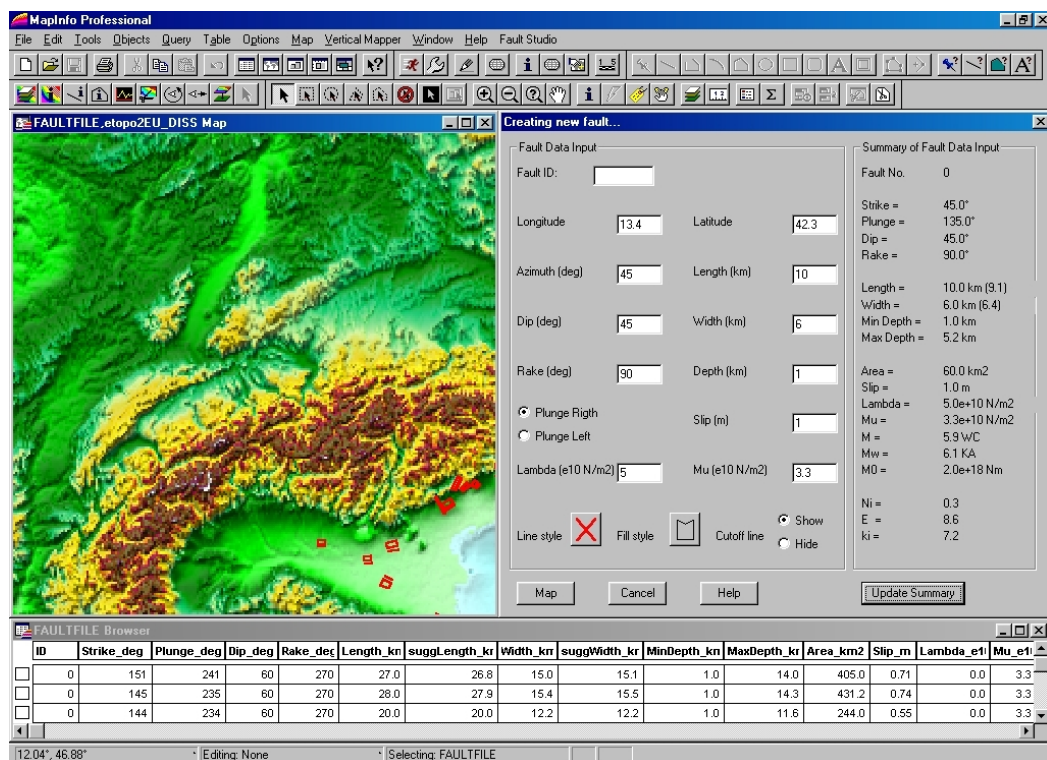


Figure 5

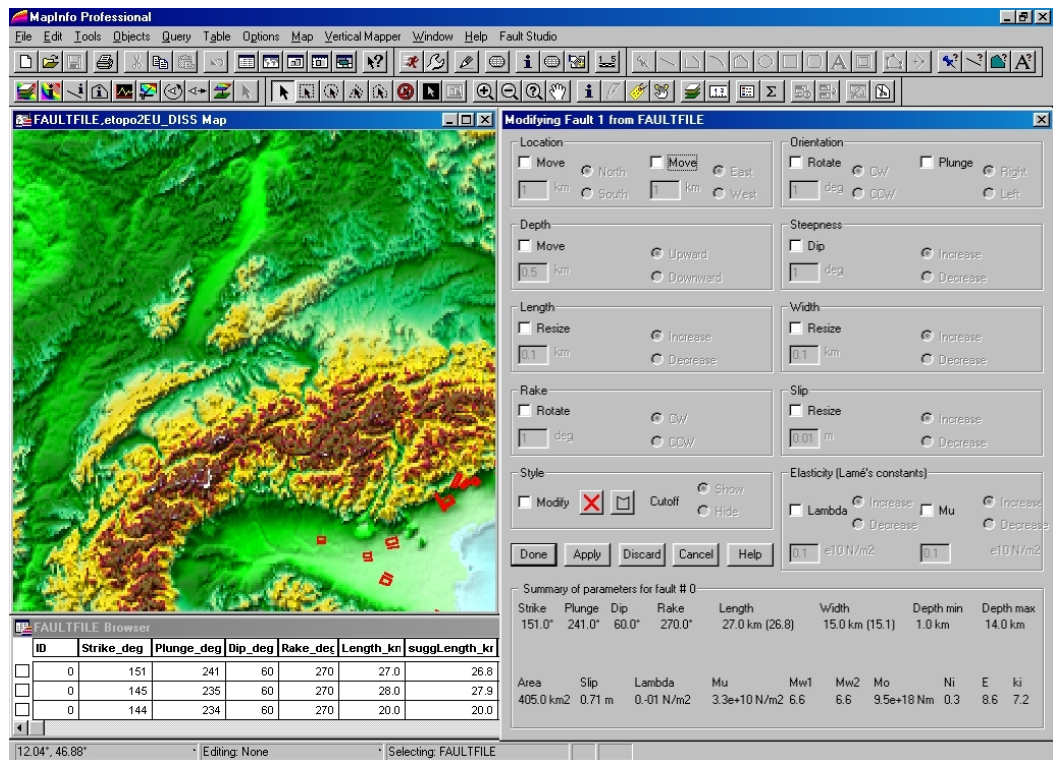


Figure 6

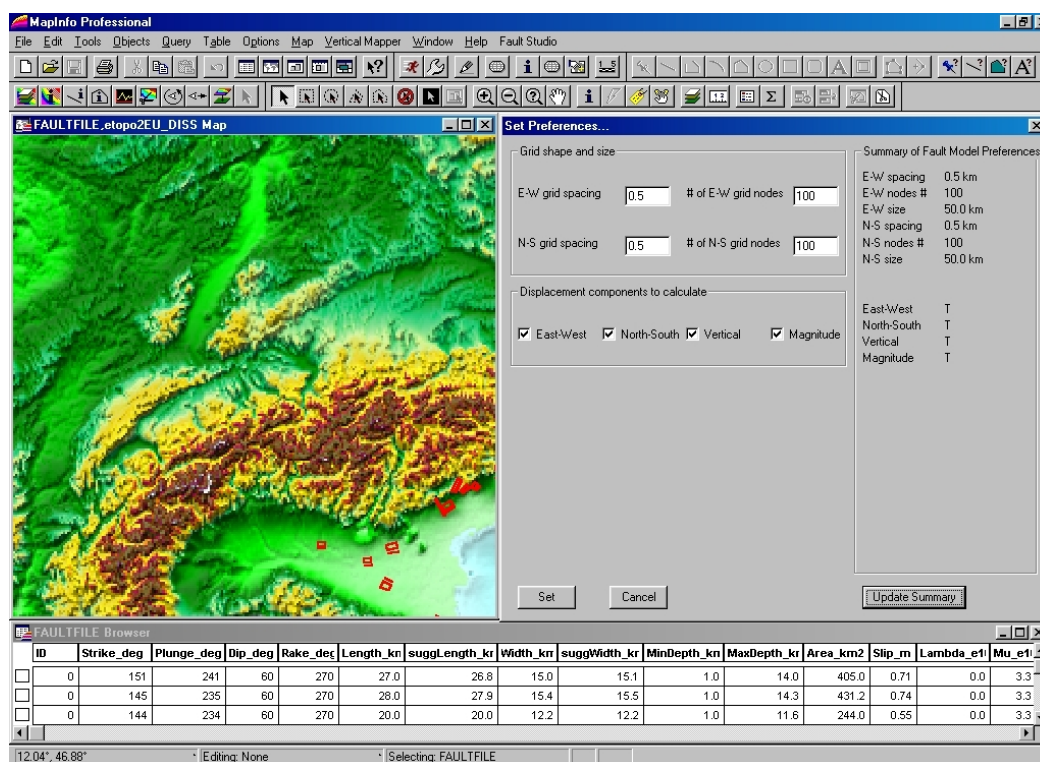


Figure 7

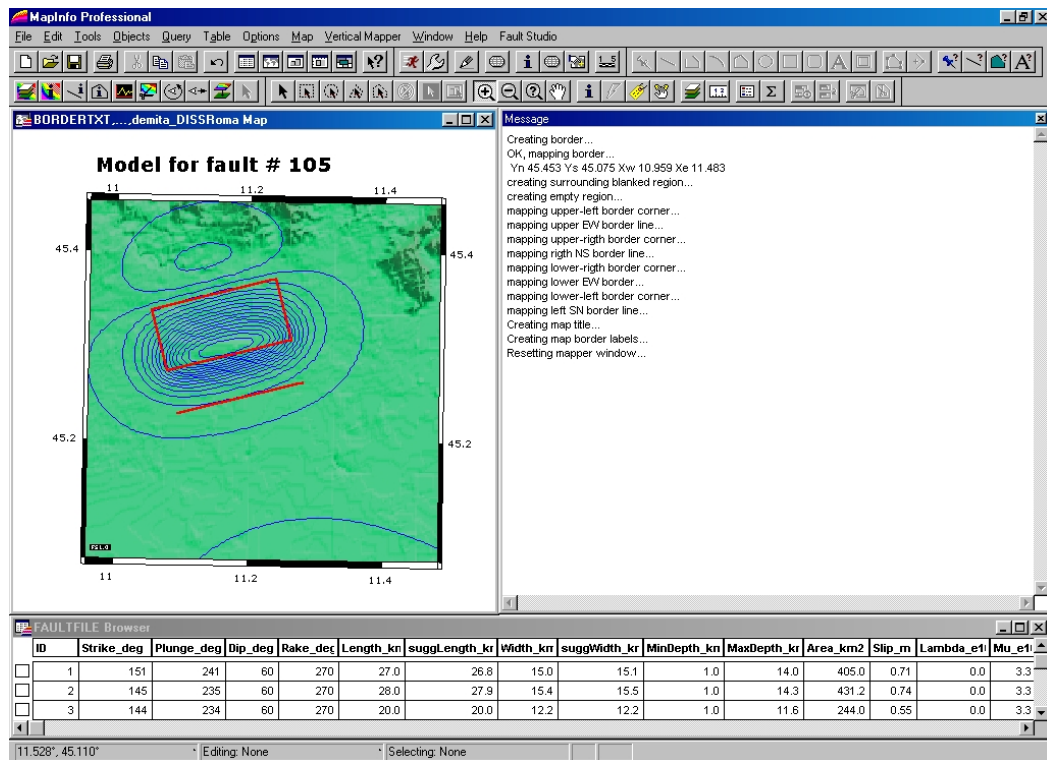


Figure 8

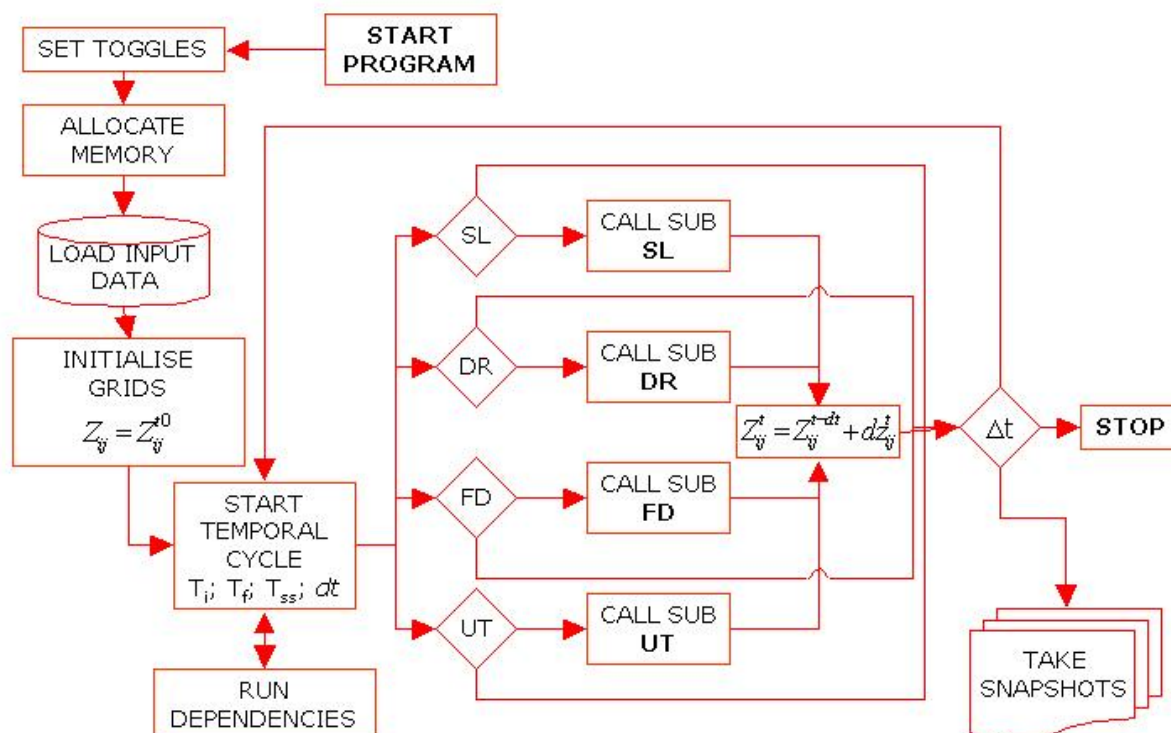


Figure 9

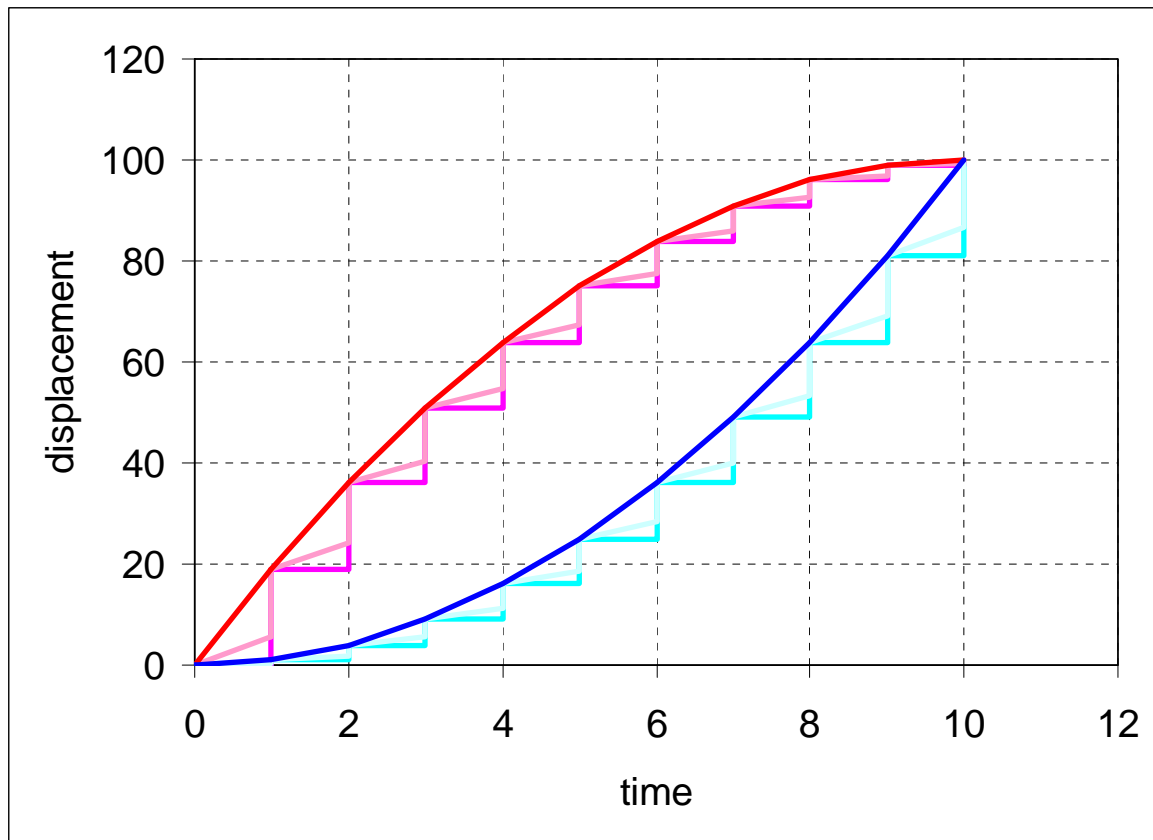




Figure 10

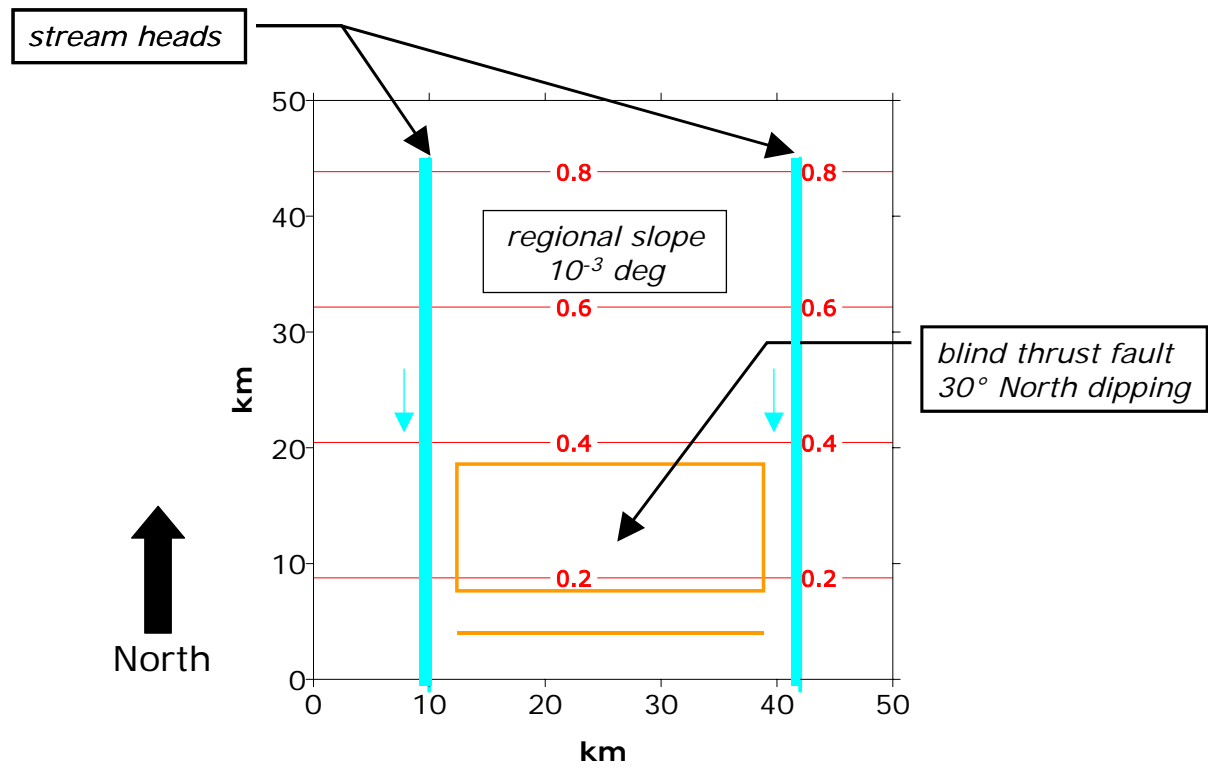


Figure 11

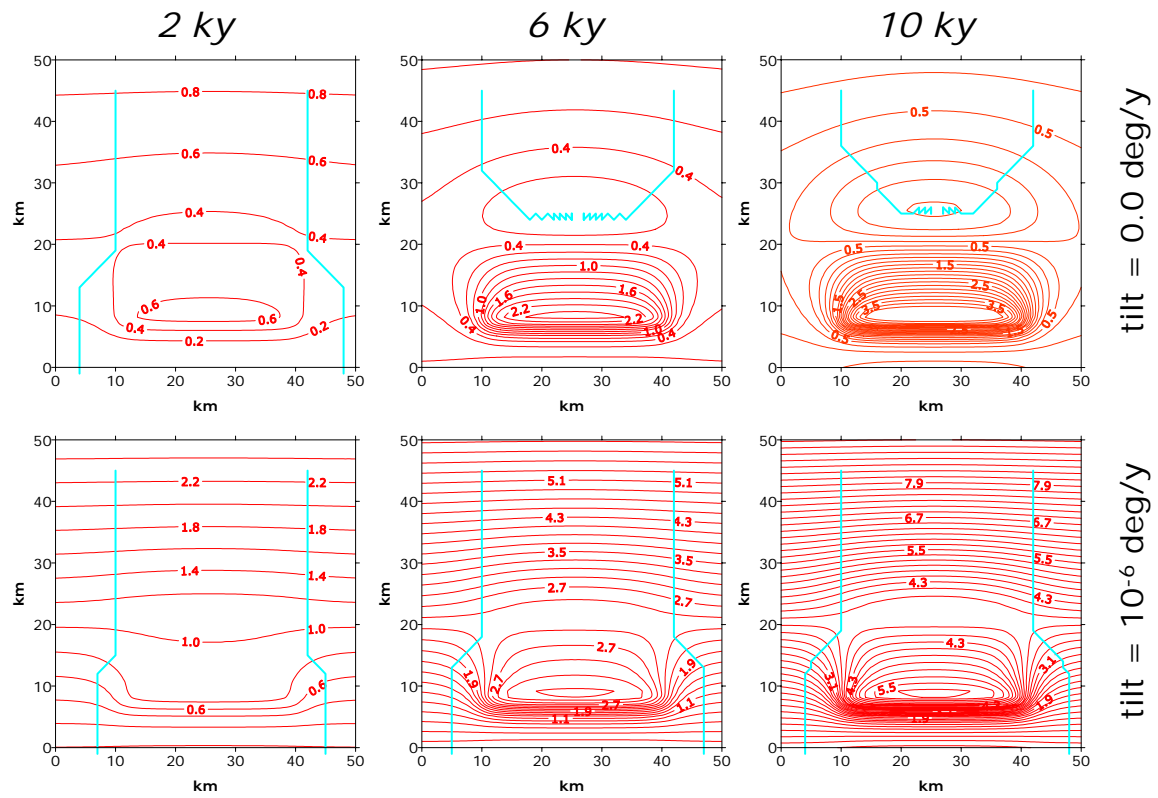


Figure 12

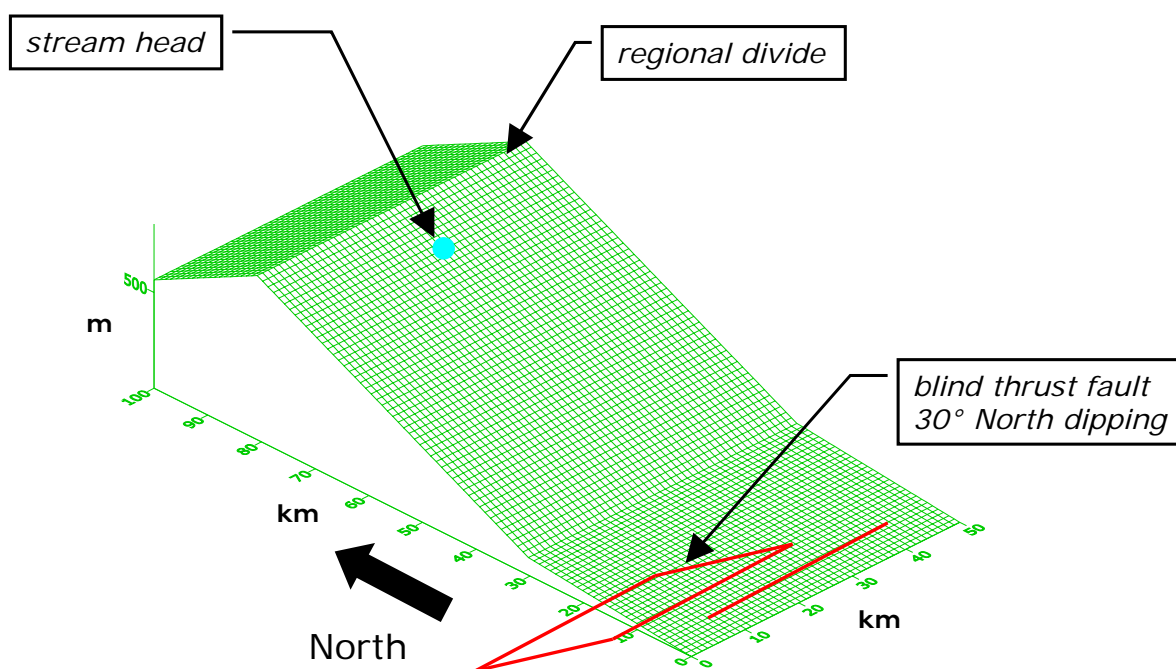


Figure 13

